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Fiber-optical sensors based on mono-crystal films of garnet ferrites for mechatronic systems

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Abstract

This work is devoted to the experimental investigation of the magneto-optical properties of yttrium-iron garnet used as a sensitive element of a fiber-optical magnetic field sensor. The block diagram of the experimental stand and methods of measurement are described. The magneto-optical effect in some YIG samples with different thickness of epitaxial layer is studied, presence of a magneto-optical properties hysteresis is established and its value is measured. Design recommendations for the developed sensor are given.

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Keywords: Ferrite-garnet;Magneto-optical effect;Sensitive element;Fiber-optical sensor;Magnetic field;Polarizer.

1. Introduction

The fiber-optical sensors (FOS) are perspective in systems working in high fire and explosion conditions. Their advantage consists in a basic electro neutrality, i.e. in lack of electric signals in close proximity to a measurement point. FOS can be based on the magneto-optical effect (rotation of the plane of polarization of electromagnetic waves in substance under the influence of a longitudinal magnetic field). It is established that this effect is most strongly shown in single-crystal films of garnet ferrites with bismuth addition (BI:FG-films) for the visible range of

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wavelengths. It is also necessary to note that sensitive elements based on thin BI:FG-films can have the small sizes and poorly influence on distribution of a magnetic field in wave guides [1].

Mono-crystal films of garnet ferrites with addition of bismuth represent the transparent mono-crystal layers, which are grown up by method of a liquid-phase epitaxy on nonmagnetic substrate. Magnetic and magneto-optical properties of BI:FG-films can be regulated over a wide range by change of conditions of receiving, composition and the subsequent processing. The best material is the garnet ferrite with $R_{3-x}Bi_xFe_{5-y}M_yO_{12}$, where R_{3-x} – a combination of rare-earth elements; M-GA, Al and micro additives of elements with the blank d-cover. The working layer of BI:FG 1-100 microns thick is grown up by method of a liquid-phase epitaxy on a rigid flat transparent plate (substrate) of nonmagnetic gadolinium - gallium garnet of $Gd_3Ga_5O_{12}$ about 0,5 mm thick.

BI:FG-films possess abnormally big specific rotation of the plane of polarization of light and high transparency. Magneto optical BI:FG properties depend, generally from the content of bismuth. The most important characteristic of magneto optical BI:FG-films is their magnetic anisotropy. Position of the directions of easy magnetization in a film is defined by a minimum of anisotropic part of the free energy including energy of cubic anisotropy of E_C, mono-axial anisotropy of E_U, interaction energy of a magnetic with an external magnetic field of $E_m = -(M, H)$ and energy of a magnetic in own degaussing field $E_d = -(M, H_d)/2$, where H_d - own degaussing field. For thin films at orientation of a vector of M along a normal to the film plane E_d value is maximum $E_d(\max) \cong 2\pi M_S^2$ and close to zero at orientation of M in the sample plane.

The purpose of experimental research consists in determination of optical properties of the BI:FG-films created by various technologies for their use in FOS.

2. Experimental research

2.1. Description of the experimental stand

The block diagram of the experimental stand for research of magneto-optical properties of BI:FG-films is given in Fig. 1. The laser light-emitting diode (LED) is powered from the power supply unit PSU1 and through multimode connecting optical fiber MM are created by the collimated beam of light with circular polarization with a wavelength of 650 nm and power of 5mW. The light beam passes through the film polarizer (FP) and BI:FG (YIG). FP and BI:FG are rigidly fixed in one rotary frame by means of which the initial corner of polarization of a beam of light is set. Further the beam of light is reflected from a mirror and divided by the Wollaston prism (WP) into two components with orthogonal polarization $\vec{E}_{YIGx}$ and $\vec{E}_{YIGy}$. The digital video camera with a CCD measures intensity of these light streams. The video camera is connected to the personal computer (PC) by means of which control of parameters of a video camera (permission, the frequency of shots, hold time, balance of color, gain) and digital processing of a video stream is made. The mirror (M) is tuned at an angle 45 degrees for minimization of a gap between the permanent magnet (PM) and BI:FG. Gap size between PM and BI:FG is adjusted by means of the motorized screw (MS) 8MS00-25 of Standa firm with the permission on a step of 1,25 microns and with a range of movement of 25 mm. For management of MS the controller of the step engine (CSE) 8SMC3-RS232 of Standa firm is used. By means of the personal computer, movement parameters are programmatically set: the direction of movement, quantity of steps for one movement and number of movements. With change of a gap between PM and BI:FG the value of intensity of a magnetic field changes and, respectively, in a BI:FG-film there is a turn of the plane of polarization [2,3]. Value of intensity of a magnetic field is registered the Honeywell SS495A1 Hall sensor (HS) located in close proximity to BI:FG. HS connected to the power supply unit (PSU2) provides measurement of induction of a magnetic field in the range (-670... +670) Gauss at sensitivity of 3.125 mV/Gs. The digital voltmeter V transfers voltage from the Hall sensor to the PC computer. The program created in the Matlab2010 software makes management of MS, record of indications of the voltmeter and processing of a video stream. Processing of a video stream and control of parameters of a video camera is carried out by means of Image Acquisition Toolbox which is built in Matlab2010 [4].

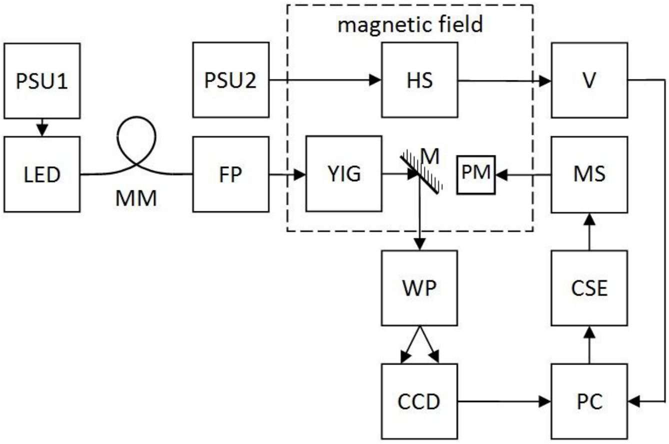


Fig. 1. Block diagram of the experimental stand.

The principle of work of an optical path including an LED, MM, FP, BI:FG and WP is displayed in Fig. 2. The film polarizer of FP from light with circular polarization separates $\vec{E}_P$ component. Under the influence of a longitudinal magnetic field $\vec{B}$ in a BI:FG-film there is a turn of the plane of polarization $\vec{E}_P$ on a angle Θ. WP divides a beam with polarization $\vec{E}_{YIG}$ on two beams with orthogonal polarization $\vec{E}_{YIGx}$ and $\vec{E}_{YIGy}$. Depending on value of induction of the magnetic field $\vec{B}$ induced at BI:FG the polarization plane angle of rotation Θ changes, and, respectively, the ratio between $\vec{E}_{YIGx}$ and $\vec{E}_{YIGy}$ vectors is changing.

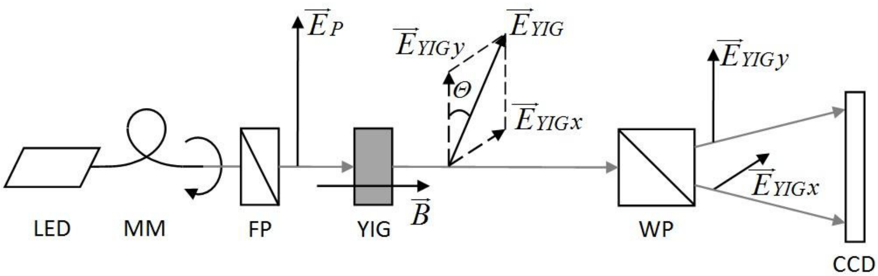


Fig. 2. Scheme of an optical path of the experimental stand.

2.2. Technique of carrying out experiment

During the experiment, a certain sequence of actions is carried out. Installation of the studied BI:FG sample in lack of PM is originally made. By means of a rotary frame of FP we achieve the maximum intensity of one of light spots on a CCD. Thus, pixels of a CCD should not go to saturation. Observance of this condition is provided with adjustment of hold time of a video camera in the operating program.

Then the angle of initial polarization of FP is adjust so that the intensities of light streams with orthogonal polarization will be equal.

Then PM on MS is mounted.

In the operating program the direction, range and number of movements of the MS are set. Start of the stand is made. After each movement the gap between PM and BI:FG decreases.

The CCD matrix registers change of values of the streams intensities falling on it. Results of measurements are automatically entered in the table.

For reduction of additive and multiplicative components of an error of measurements the program counts the relation of values of streams intensities according to a known formula (1):

$$Y = \frac{I_1 - I_2}{I_1 + I_2}, \tag{1}$$

where Y - the relation of values of light streams; I_1 - value of a stream of the first ray of light; I_1 - value of a stream of the second ray of light.

Then program poll of the digital voltmeter is carried out. Value of intensity of the magnetic field operating on BI:FG is calculated according to a known formula (2):

$$H = \frac{4\pi \cdot 10^{-3} \cdot (U - U_{amf})}{\mu \cdot \mu_0 \cdot S}, \tag{2}$$

where H is intensity of a magnetic field, Oe;

U is output voltage of the sensor of the Hall, V;

U_{amf} is output voltage of the sensor of the Hall in the absence of influence of a magnetic field, V;

$\mu = 1.000038$ is magnetic permeability of air;

$\mu_0 = 1.25663706 \cdot 10^{-6}$ is magnetic permeability of vacuum;

$S = 31.25$ V/T - sensitivity of the sensor of the Hall.

MS begins the reverse movement for definition of a hysteresis of magneto optical properties of BI:FG at achievement of the minimum gap between BI:FG and PM.

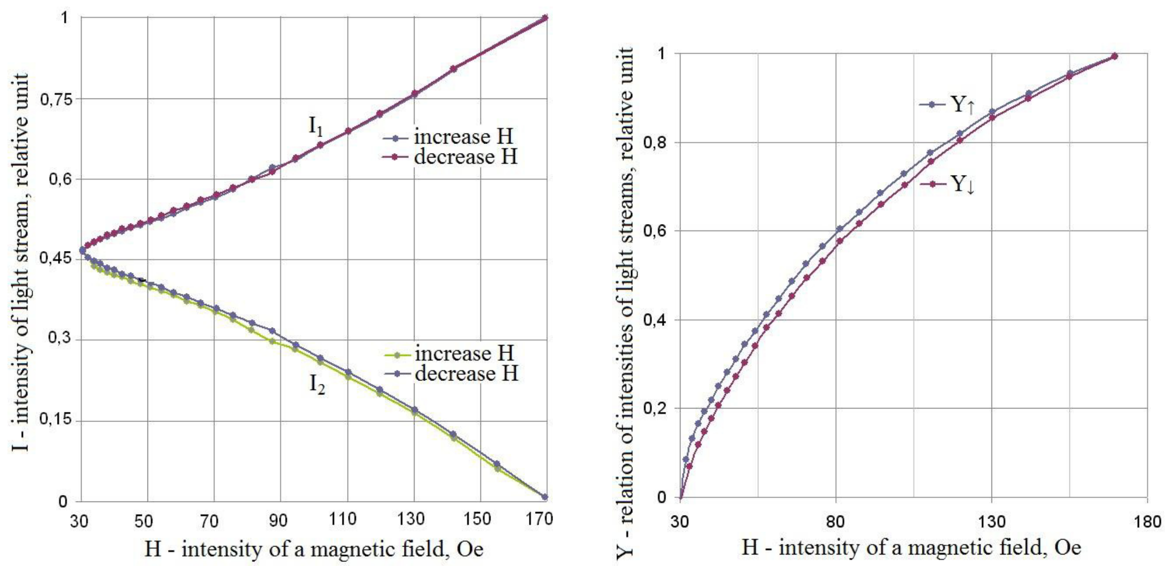
According to results of measurements the graphic dependences are plot: $I_{1\uparrow}(H)$, $I_{1\downarrow}(H)$, $I_{2\uparrow}(H)$, $I_{2\downarrow}(H)$ - intensities of the first and second light streams at the forward and reverse movement of MS, respectively; $Y_{\uparrow}(H)$, $Y_{\downarrow}(H)$ - the relation of intensities of light streams at the forward and reverse movement of MS, respectively.

2.3. *Results of measurements*

Researches of magneto-optical properties (sensitivity, hysteresis, linearity range, transmission) of samples of BI:FG of the ShOTA 8-12 brand $(Bi, Lu, Gd)_3(Fe, Ga)_5O_{12}$, 4πMs=950 Gs, Hs=500 Oe, FUShchI 75-262 $(Bi, Lu)_3(Fe, Ga)_5O_{12}$, 4πMs=350 Gs, Hs=85 Oe, YuL 8-1 $(Bi, Y)_3(Fe, Ga)_5O_{12}$, 4πMs=100 Gs, Hs=30 Oe, grown up in scientific research institute of Materials science, Zelenograd were conducted. Experimental dependences for these samples are given in Fig. 3-5. Results of measurements are given in Table 1.

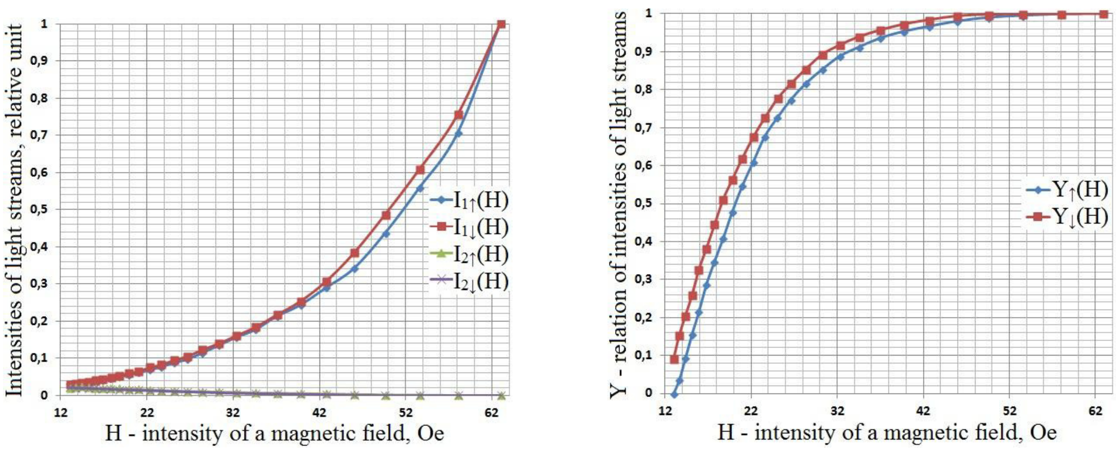
Table 1. Experimental characteristics of samples of BI:FG.

BI:FG brand	Range of sensitivity (Oe)	Rangeofresearches (Oe)	Sensitivity (1/Oe)		Hysteresis (Oe)	
			For $I_{1\uparrow}$	For $Y_{\uparrow}$	For $I_{1\uparrow}$	For $Y_{\uparrow}$
ShOTA 8-12	0-500	30-170	0.008	0.01	8	0.2
FUShchI 75-262	0-85	12-65	0.06	0.07	2	1
YuL 8-1	0-30	12-65	0.053	0.09	16	10



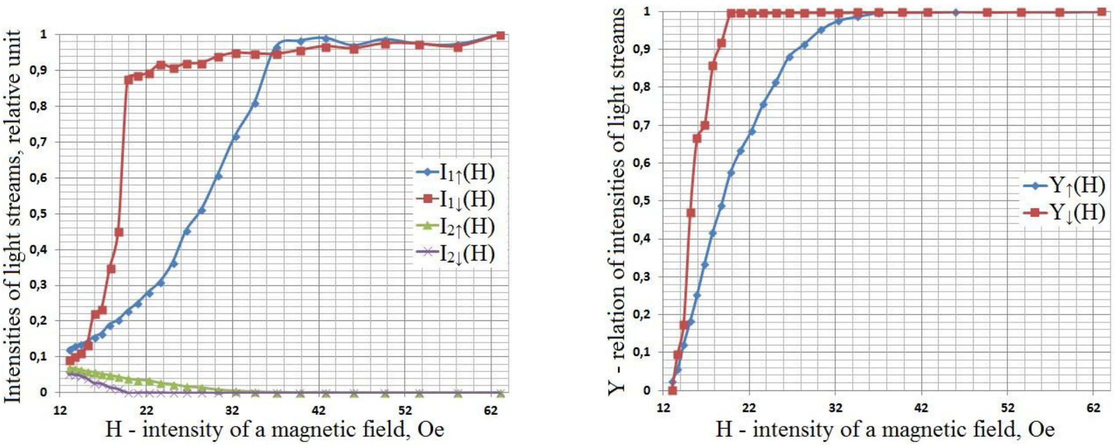
(a) (b)

Fig. 3. Magneto-optical properties of a sample of BI:FG of the ShOTA 8-12 brand (Hs=500 Oe): (a) dependence of light streams of I_1, I_2 on intensity of a magnetic field; (b) dependence of a difference of streams of Y on intensity of a magnetic field.



(a) (b)

Fig. 4.Magneto-optical properties of a sample of BI:FG of the FUShchI 75-262 brand (Hs=85 Oe): (a) dependence of light streams of I_1, I_2 on intensity of a magnetic field;(b) dependence of a difference of streams of Y on intensity of a magnetic field.



(a) (b)

Fig. 5. Magneto-optical properties of a sample of BI:FG of the YuL 8-1 brand (Hs=30 Oe): (a) dependence of light streams of I_1, I_2 on intensity of a magnetic field;(b) dependence of a difference of streams of Y on intensity of a magnetic field.

The hysteresis of magneto optical BI:FG properties is caused, generally by change of strip domain structure of BI:FG at forward and reverse change of intensity of a magnetic field [5]. Magnetic properties of films of micron thickness can be defined by their properties interface film substrate [6]. Change of domain structure leads to additional change of a transmission. The images of strip domain structure of BI:FG of the YuL 8-1 brand (Hs=30 Oe) received by means of a microscope Biomed-5P with a lens 20x are shown in Fig. 6. In the absence of a magnetic field ratio of the light and dark fields BI:FG (Fig. 6(a)) the approximately identical. At influence of strong magnetic fields the area of dark strips is minimum (Fig. 6(b)), and the plate of BI:FG becomes the most transparent for the passing beam of light.

(a) (b) (c)

Fig. 6. A view of structure of BI:FG of the YuL 8-1 brand in a polarizing microscope: (a) strip domain structure in lack of a magnetic field; (b) strip domain structure at influence of a magnetic field (the middle of working range); (c) strip domain structure in a stronger magnetic field (the mode of saturation of structure).

The block diagram of the experimental stand for research of temperature stability of BI:FG is shown in Fig. 7. Here the crystal of BI:FG was located in the center of the solenoid creating a magnetic field. All this design was located in the climatic camera ЗИКО КХТВ 64 М. Test is carried out in the temperature range from minus 50 ^0C to plus 50 ^0C with a step 10 ^0C. Current of power supply of the solenoid $\boldsymbol{i}$ in the range from zero to 0.08 A changed with a step 0.01 A that corresponds to change of intensity of a magnetic field H from zero to 160 Oe.

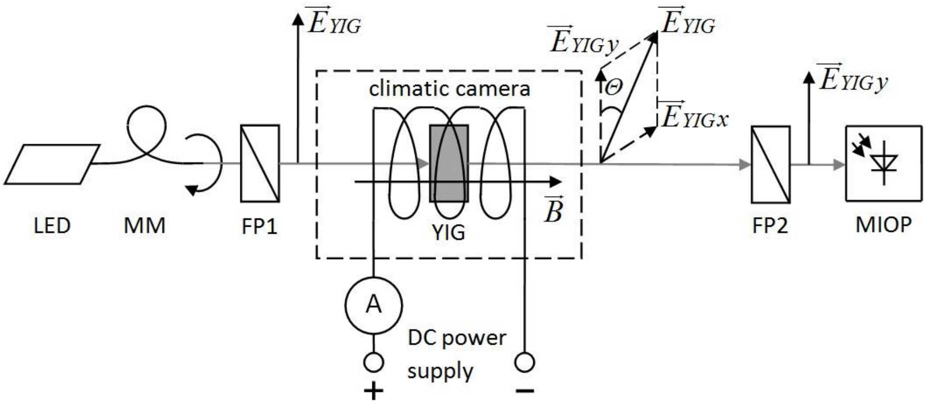


Fig. 7. The scheme of the experimental stand for measurement of temperature stability of BI:FG.

Temperature dependences of optical power of Y registered by the measuring instrument of optical power (MIOP) for BI:FG of the ShOTA 8-12 brand are shown in Fig. 8.

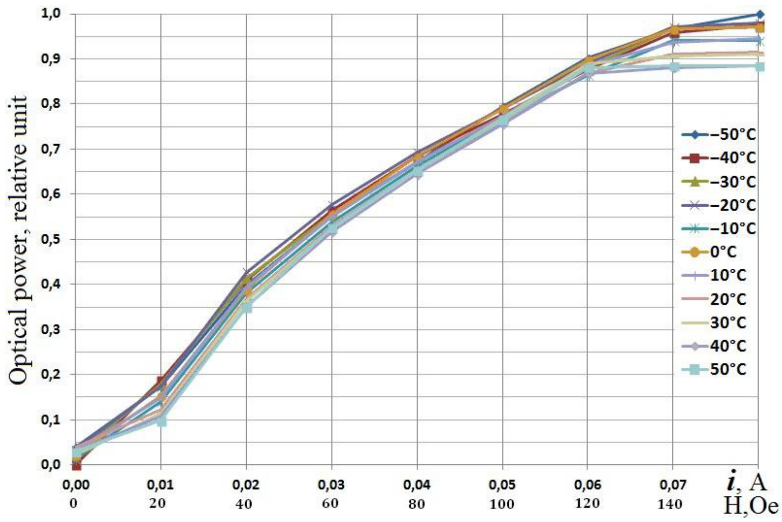


Fig. 8. Influence of temperature on the adjusting characteristic of a transmission of YIG.

With growth of temperature BI:FG transmission decreases. Temperature coefficient of change of a transmission is about 0.06%/degree.

3. Conclusion

Follows from results of the conducted researches that:

• Crystals of BI:FG can be used for realization of sensitive elements of optical sensors of a magnetic field of high sensitivity; linearity and sensitivity of the characteristic of Faraday rotation significantly depends on composition of a mono-crystal film; presence of a magneto-optical properties hysteresis is established and its value is measured; further development of manufacturing technology of BI:FG has to be directed on reduction of a hysteresis of magneto optical BI:FG properties, especially for highly sensitive crystals with small induction of saturation;

• Temperature dependence of coefficient of a transmission of films is investigated; it is revealed that for the studied samples it decreases approximately by 0.06% /degree; further development of manufacturing technology of BI:FG is necessary for improvement of temperature stability of BI:FG;

• Further development of manufacturing technology of BI:FG is necessary for increase in Faraday rotation and reduction of optical absorption of BI:FG-films for effective use of the studied materials in fiber-optical sensors.

References

[1] V.Sh. Berikashvili, V.S. Chizhov, M.Ya. Yakovlev. Fiber sensors on the the base of YIG with BI films for measurements of magnetic field and current. Journal of radio electronics. [serial online] N4 – 2002 April 1995 [cited 2014 September 3]. Available from: URL: http://jre.cplire.ru/jre/apr02/1/text.html.

[2] B.A. Gizhevskii and other, Optical and Magneto Optical Properties of Nanostructured Yttrium Iron Garnet. Physics of the Solid State, v.51, 2009, pp.1836-1842.

[3] V.V. Randoshkin, A.Ya. Chervonenkis, Prikladnaya magnitooptika [Applied magnetooptics]. Ehnergoatomizdat, Moskva, 1990. (in Russian)

[4] I.M. Zhuravel', Image Acquisition Toolbox. Available from: URL: http://matlab.exponenta.ru/imageacquis/index.php, [accessed 30 December 2014].

[5] A.L. Khvalin, A generalized model of magnetic stripe domain microstructure in theyttrium-iron garnet films, Bulletin of PNU [serial online] N1 (28) – 2013 [cited 2014 September 3]. Available from: URL: http://pnu.edu.ru/vestnik/pub/articles/1765/en/.

[6] Shaposhnikov A.N., Berzhansky V.N., Prokopov A.R. et al. Interface properties single crystal films bismuth-constituted garnet – GGG substrate Scientific Notes of Taurida National V.I. Vernadsky University Series: Physics 2009; 22(61): 1–127.